Optical Noise Reduction Apparatus and Method

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5  Field of the Invention

This invention relates generally to optical communications systems. More specifically, the invention relates to the signal-to-noise ratio of optical signals in communications systems, and to devices and methods for

10  increasing the signal-to-noise ratio of such signals.

Background of the Invention

In optical systems the signal-to-noise ratio (SNR) of an optical signal tends to degrade as it propagates through optical media such as optical waveguides or optical fibers.

15  The SNR of the optical signal may also degrade when the optical signal propagates through optical devices such as multiplexers. Opto-electronic regenerators can be used to improve the SNR of the optical signal but these devices are costly and inefficient. Erbium-doped fiber amplifiers (EDFAs) have been

20  used to amplify weak optical signals without opto-electronic conversion. However, the amplification process adds noise causing SNR degradation. Noise performance in optical amplifiers is typically measured by the noise figure (NF) which is defined as the ratio of the SNR at the input of the optical

25  amplifier to that at the output of the optical amplifier ($NF = SNR_{in} / SNR_{out}$). Under ideal conditions, a fiber amplifier may be fully inverted and the theoretical lower limit on the NF is 3 dB. This corresponds to the quantum limit of the NF. This quantum limit of the NF has limited the effectiveness of

30  fiber amplifiers. Some optical amplifiers [R.A. Griffin, P.M. Lane, and J.J. O'Reilly, "Optical amplifier noise figure

reduction for optical single-sideband signals," Journal of Lightwave Technology, Vol.17, No.10, 1999, pp.1793-1796.] are used for NF reduction of optical single-sideband signals only and are not suited for other data-format signals and multi-

5   channel optical signals.  Other optical amplifiers [S.  Lee, "Low-noise fiber-optic amplifier utilizing polarization adjustment," U.S.  Patent, No.  5790721, Aug.  4, 1998] [Y.C.Jung and C.H.Kim, "Optical Fiber Amplifer using Synchronized Etalon Filter", U.S. Patent No. 6,181,467, January

10   30,2000] [D.J.  DiGivanni, J.D.  Evankow, J.A.  Nagel, R.G. Smart, J.W.  Sulhoff, J.L.  Zyskind,  "High power, high gain, low noise, two-stage optical amplifier," U.S.  Patent, No. 5,430,572, July 4, 1995.] have been developed to lower the NF but they are all constrained by the 3 dB quantum limit.

15   Summary of the Invention

A noise reduction apparatus is provided which increases the signal-to-noise ratio (SNR) of an input optical signal.  To increase the SNR, the noise reduction apparatus makes use of the coherence of a coherent component of the input

20   optical signal having a coherent signal power and the incoherence of an incoherent component of the input optical signal having an incoherent signal power.  The input optical signal is split in two path signals with each path signal having the same intensity but a different phase.  The phase

25   difference is tuned in a manner which produces a main output optical signal containing most of the coherent signal power and containing a fraction of the incoherent signal power, with the remaining incoherent signal power being diverted to one or more subsidiary outputs.

30   One broad aspect of the invention provides a method of reducing incoherent signal power, in an input optical signal containing a coherent component having a coherent signal power

and an incoherent component having the incoherent signal power. The method involves splitting the input optical signal into $M$ path signals each having a respective coherent path component and a respective incoherent path component. A respective phase

5    adjustment is applied to at least one, and preferably $M-1$ or $M$ of the $M$ path signals. The phase adjustments are applied such that at a combination point, the coherent path components are combinable constructively and each incoherent path component is substantially uncorrelated with each other incoherent path

10    component. At the combination point, the $M$ path signals are recombined to produce an output optical signal with an improved SNR.

In some embodiments, combining the $M$ path signals to produce an output optical signal with an improved SNR involves

15    coupling the $M$ path signals together in a manner which produces the output optical signal containing most of the coherent signal power and containing a fraction of the incoherent signal power, with the remaining incoherent signal power being diverted to one or more secondary outputs.

20    The phase adjustments may be achieved using any suitable techniques. For example, the phase adjustments may be achieved by employing an optical path length difference, $\Delta L_o$, between any two consecutive signals of the $M$ path signals which substantially satisfies $\Delta L_o > L_c$ wherein $L_c$ is the coherence

25    length of the incoherent path components of the $M$ path signals. It is noted that the optical path length difference, $\Delta L_o$, is a function of physical path length difference and/or index of refraction difference, when present. The optical path length difference, $\Delta L_o$, may result from using different physical path

30    lengths and/or using paths made of optical transmission media having different indices of refraction. Fine phase adjustments to one or more of the path signals may be applied using phase

controllers such as heaters, or piezoelectric devices to name a few examples.

To further improve the SNR, the splitting, the phase adjustment and the combining may be iterated $N$ times wherein $N$
5   satisfies $N \geq 2$. This method may result in an improvement of the SNR by a factor of approximately $M^N$.

The optical path length difference, $\Delta L_o$, may be chosen to satisfy a symbol spread tolerance. Preferably, the optical path length difference substantially satisfies $\Delta L_o \leq \chi C/R$ where $C$
10   is the speed of light in vacuum; $R$ is the symbol rate of the optical signals and $\chi$ is a fraction indicating a symbol spread to which the system is tolerant. For example, $\chi = 0.2$ indicates a 20% tolerance.

In some embodiments, the splitting, combining and
15   phase adjustment may be performed with a Mach-Zehnder interferometer-based structure.

For multi-channel applications, the method may be applied to an optical signal having a plurality of equally spaced channels such that $\Delta L_o = KC/(2\,\Delta f)$ where, $\Delta f = f' - f$ and, $f'$
20   and $f$ are the frequencies of two consecutive channels of the input optical signal where K=1,2,3,.... In this embodiment, preferably $\Delta L_o$ is selected to satisfy the coherence length and symbol spread constraints through the appropriate selection of K.

25   Another broad aspect of the invention provides a noise reduction apparatus adapted to improve signal-to-noise ratio in an input optical signal having a coherent component and an incoherent component. The apparatus has an input optical splitter, two optical transmission media, and an output
30   optical coupler. The input optical splitter might for example

be a 1x2 single-mode optical coupler.  The transmission media might be fibers or waveguides for example.  The output optical coupler might for example be a 2x2 single-mode optical coupler. The input optical splitter is adapted to split the input

5   optical signal into two path signals each having a respective coherent path component and a respective noise path component. Each one of the two path signals propagates through a respective one of the two optical transmission media.  A phase controller is provided in at least one, and preferably both of

10   the optical transmission media adapted to apply a phase adjustment to a respective one of the two path signals.  The phase adjustment applied by the phase controller, and an optical path length difference, $\Delta L_o$, between the two optical transmission media are selected such that the noise path

15   components are substantially uncorrelated with each other at the output optical coupler.  The output optical coupler couples the path signals such that substantially all of the coherent signal is produced at a first output, while the noise component is substantially divided between the first output and a second

20   output.  In some embodiments, the NF may be further improved by including a further noise reduction apparatus within each one of the $M$ paths.  These further noise reduction apparatuses might be used to improve the SNR of a respective one of the $M$ path signals before the path signals are recombined.

25          Another embodiment of the invention provides a noise reduction apparatus adapted to improve SNR in an input optical signal having a coherent component and an incoherent component. The noise reduction apparatus has an optical coupler, two optical transmission media, and two reflectors.  The optical

30   coupler might be a 2x2 single-mode coupler and the reflectors might be broadband fiber gratings or gold tip pig tail fiber reflectors.  The optical coupler is adapted to split the input optical signal into two path signals each having a respective

coherent path component and a respective incoherent path
component, wherein each one of the two path signals propagates
through a respective one of the two optical media to a
respective one of the two reflectors where the respective path

5   signal is reflected, and propagates back through the respective
one of the two optical media to the optical coupler. There is
at least one phase controller adapted to a respective phase
adjustment to at least one of the two path signals wherein the
respective phase adjustment is applied in a manner that at the

10  optical coupler the coherent path components are coupled
substantially into a single output of the optical coupler, and
the incoherent component is coupled to multiple outputs.

Another broad aspect of the invention provides a
method of designing a noise reduction apparatus. The method

15  includes identification of a single frequency of interest,
preferably a number of equally spaced frequencies. The method
includes determining the minimum and maximum allowable values
of an optical path length difference, $\Delta L_o$, between any two of $M$
path signals such that incoherent path components of the any

20  two of $M$ path signals are substantially not correlated and
satisfy a symbol spread tolerance, respectively.

In some embodiments, the method may include selecting
a phase difference between any two of $M$ path signals such that
the optical path length difference, $\Delta L_o$, associated with the

25  phase difference is greater than the minimum allowable value
and smaller than the maximum allowable value. Preferably, the
process of selecting a phase difference involves $\Delta L_o$ satisfying
$\Delta L_o > L_c$ where $L_c$ is the coherence length of the $M$ path signals.
Preferably, the process of selecting a phase difference

30  involves $\Delta L_o$ satisfying $\Delta L_o \leq \chi C/\omega$ where $C$ is the speed of light
in vacuum, $\omega$ is the carrier data rate of an input optical
signal and $\chi$ is a symbol spread tolerance. For single

wavelength applications, the phase difference preferably satisfies $\delta = 2p\pi$, where $p = 0, \pm1, \pm2, \ldots$. For multiple wavelength applications the phase difference preferably satisfies $\Delta L_o = KC/(2\Delta f)$ where $\Delta f = f' - f$ and, $f'$ and $f$ are the frequencies of two consecutive channels.

A broad aspect of the invention provides a noise reduction apparatus for improving the signal-to-noise ratio of an optical signal, having an input optical splitter adapted to split the optical signal into M path signals transmitted along respective M optical transmission paths, wherein M>=2. A phase adjustment device is provided in at least one of the M optical transmission paths adapted to apply a phase adjustment relative the M path signals. An output optical coupler is provided which is adapted to combine the M path signals into an output optical signal having a portion of incoherent components of each of the M path signals substantially uncorrelated and having coherent components of each M path signal constructively combined.

Another broad aspect of the invention provides a method of improving the signal-to-noise ratio of an optical signal which involves splitting the optical signal into a plurality of path signals, each path signal having a coherent path component and an incoherent path component, adjusting the phase of at least one of the plurality of path signals such that, at a combination point, the coherent path components are combinable constructively and each incoherent path component is substantially uncorrelated with each other incoherent path component; and combining the path signals at said combination point.

The invention according to yet another broad aspect provides a noise reduction apparatus for an optical signal having an optical splitter for splitting an input optical

signal having a coherent signal component and an incoherent

signal component into a plurality of path signals transmitted

along a plurality of respective transmission paths, a phase

adjustment device associated with at least one of the plurality

5   of transmission paths for applying a phase difference between

the plurality of path signals; and an optical coupler for

combining the plurality of path signals into a main output

optical signal and at least one subsidiary output optical

signal, wherein the main output optical signal comprises

10  substantially all of the coherent signal component and the

subsidiary output signal comprises at least a portion of the

incoherent signal component.

Brief Description of the Drawings

15          Preferred embodiments of the invention will now be

described with reference to the attached drawings in which:

Figure 1 is a block diagram illustrating a noise

reduction apparatus, which is used to increase the signal to

noise ratio (SNR), provided by a first embodiment of the

20  invention;

Figure 2 is a block diagram illustrating a noise

reduction apparatus in which $N$ noise reduction apparatuses of

Figure 1 are connected in series, provided by a second

embodiment of the invention;

25          Figure 3 is a block diagram illustrating a noise

reduction apparatus, which is used to increase the SNR,

provided by a third embodiment of the invention;

Figure 4 is a block diagram illustrating a noise

reduction apparatus, which is used to increase the signal to

noise ratio (SNR), provided by a fourth embodiment of the invention; and

Figure 5 is a flow chart of the method used to design the noise reduction apparatus of Figure 1.

5 Detailed Description of the Preferred Embodiments

Referring to Figure 1, shown is a schematic block diagram illustrating a noise reduction apparatus 10, which is suitable for both single and multi-channel optical systems. The noise reduction apparatus 10 has an input 5 connected to an

10 input optical splitter 40 having one input and two outputs (for example, a 1x2 coupler). The two outputs of the input optical splitter 40 are connected to respective inputs of an output optical coupler 70 through first and second optical transmission media 41,42 respectively. The output optical

15 coupler 70 has two inputs, a main output 85, and a subsidiary output, 81 (for example a 2x2 coupler). The optical transmission media 41 and 42 are equipped with respective phase controllers 50 and 60. The main output 85 of the output optical coupler 70 constitutes the output of the noise

20 reduction apparatus 10. The subsidiary output 81 of the output optical coupler 70 is terminated locally.

The noise reduction apparatus 10 of Figure 1 reduces noise by exploiting the coherence of an optical signal and the incoherence of the noise within the optical signal. In

25 particular, according to the invention, an input optical signal $S_{IN}$, which includes a coherent component having intensity $I_C$ and an incoherent component (the noise) having intensity $I_N$, is split by the input optical splitter 40 into two path signals $S_1, S_2$ that propagate along the optical transmission media 41,42

30 respectively. By "incoherent component" it is meant generally any unwanted component of the input signal $S_{in}$ which can be

reduced in power by the apparatus 10, typically noise. Each path signal $S_1, S_2$ has a respective coherent path component having intensity $I_C/2$ and a respective incoherent (noise) path component having intensity $I_N/2$. The phase difference in the

5  optical path lengths of the two optical transmission media 41,42, including the effects of the phase controllers 50,60 and including the effect of the input optical splitter 40, is selected such that path signal $S_1$ propagating in optical transmission medium 41 experiences a delay in time, $\Delta t$,

10  compared with the path signal $S_2$ propagating in transmission medium 42. This delay in time is equivalent to a relative phase spread for coherent signals. According to the invention, this relative phase spread is chosen such that the coherent path component of the signal propagating through optical

15  transmission medium 42 is almost completely coupled by output optical coupler 70 together with the coherent path component of the signal propagating through optical transmission medium 41 to the main output 85 in a manner that the two coherent path components interfere constructively and experience minimal

20  loss. At the same time, the incoherent path components (the noise) of the two path signals $S_1, S_2$ become substantially uncorrelated with one another and couple equally into the main output 85 and the subsidiary output 81. The coherent signal power remains largely unaffected during the process of

25  splitting and combining the two path signals with almost all of the coherent signal power being reproduced at the main output 85. On the other hand, the splitting and combining of the incoherent path component results in it being split approximately evenly between the main output 85 and the

30  subsidiary output 81. This results in a much lower noise level and consequently results in a dramatic increase in the signal-to-noise ratio (SNR).

## Theory of the Invention

At a combination point that exists at the output optical coupler 70, consider the case where there are two linearly polarized plane waves of the same wavelength, given by

$$\overrightarrow{E_1}(\vec{r},t) = \overrightarrow{E_{01}} Cos\left[\omega t - \varphi_1(\vec{r}) - \varphi_{01}\right] \quad \text{......} \ (2)$$

$$\overrightarrow{E_2}(\vec{r},t) = \overrightarrow{E_{02}} Cos\left[\omega t - \varphi_2(\vec{r}) - \varphi_{02}\right] \quad \text{......} \ (3)$$

which have propagated along the optical transmission media 41,42 and overlap at the combination point. The resultant field is simply

$$\vec{E}(\vec{r},t) = \overrightarrow{E_1}(\vec{r},t) + \overrightarrow{E_2}(\vec{r},t) \quad \text{......} \ (4)$$

neglecting a constant factor, the irradiance can be expressed as the time average of the total field:

$$I = \left\langle \left[\overrightarrow{E_1}(\vec{r},t) + \overrightarrow{E_2}(\vec{r},t)\right] \bullet \left[\overrightarrow{E_1}(\vec{r},t) + \overrightarrow{E_2}(\vec{r},t)\right] \right\rangle = I_1 + I_2 + I_{12} \text{......}(5)$$

where $I_1 = \left\langle \overrightarrow{E_1}^2 \right\rangle$, $I_2 = \left\langle \overrightarrow{E_2}^2 \right\rangle$, and $I_{12} = 2\left\langle \vec{E_1} \bullet \vec{E_2} \right\rangle = 2\sqrt{I_1 I_2} Cos\delta$ , the last

term being known as the interference term and $\delta = \varphi_1(\vec{r}) - \varphi_2(\vec{r}) + \varphi_{10} - \varphi_{20}$ being the phase difference in the plane waves at the combination point. The $\varphi_1(\vec{r}) - \varphi_2(\vec{r})$ contribution to the phase difference is due to the above discussed relative phase spread experienced by the path signal $S_1$ compared to the path signal $S_2$. The $\varphi_{10} - \varphi_{20}$ contribution is due to an initial phase difference at the initial point introduced by input optical splitter 40. When $\varphi_{10} - \varphi_{20}$ is constant, the linearly polarized plane waves are said to be coherent. For coherent waves, the overall phase difference $\delta$ is expressible as $\delta = 2\pi f \Delta t$ where $\Delta t$ is the delay in time between the two optical transmission media

41,42 including the effects of the phase controllers 50,60 and the splitter 40. On the other hand, if the two waves are incoherent as is the case with incoherent path components in particular, they do not have a constant phase difference but

5 rather have an "effective phase difference $\delta$" which varies randomly and rapidly as compared to the measuring time (in other words, an incoherent signal is substantially uncorrelated with itself a constant time later). The term "effective phase difference" is used because it does not really make sense to

10 refer to the phase of such incoherent components. The interference term $I_{12}$ is reduced to zero for such incoherent waves. Based on the above analysis, for coherent waves, when $\cos\delta=1$, i.e. when $\delta = 0, \pm 2\pi, \pm 4\pi, \ldots\ldots$, the irradiance I at the combination point has the maximum value $I_{max} = I_1 + I_2 + 2\sqrt{I_1 I_2}$. For

15 incoherent waves, the irradiance I at the overlap point is always constant value $I = I_1 + I_2$. For now, a simple rule will suffice: if the overlapping waves are coherent, their fields can combine with each other in a sustained fashion and will be added first and then squared to yield the irradiance. If the

20 waves are incoherent, the individual fields, which are effectively independent, will be squared first and then these component irradiances added.

Another way of summarizing the behaviour is to look at the power transfer function of the apparatus of Figure 1

25 which can be summarized as:

Main output = [cos$^2$($\delta$/2)] input

Subsidiary output = [sin$^2$($\delta$/2)] input

For a random phase difference $\delta$ such as is effectively the case for incoherent path components, the above can be time averaged

30 and expressed as:

Main output = input/2

Subsidiary output = input/2

For a phase difference selected to satisfy, for the coherent
path components, $\cos(\delta/2) = \pm 1$, i.e., when $\delta = 0, \pm 2\pi, \pm 4\pi, \ldots$, the
5    transfer function can be time averaged and expressed as:

Main output = input

Subsidiary output = 0.

The present invention can be used to reduce noise
power by 3-dB. At the same time, the power of the coherent
10   component of the input optical signal remains almost the same.
Eventually, the signal-to-noise ratio of the input signal is
increased by a factor of 2.

The individual components of Figure 1 will now be
described in further detail.

15   Input Optical Coupler

The function of the input optical splitter 40 is to
split the input optical signal with intensity, $I$, at its input
into two path signals having the same intensity, $I/2$, but
varying by a phase difference, $\varphi_{10}-\varphi_{20}$. In a preferred
20   embodiment of the invention, the input optical splitter 40 is a
1x2 3-dB single-mode fiber coupler, for example a fused-fiber
coupler. In another embodiment of the invention, the input
optical splitter 40 is a 2x2 3-dB single-mode fiber coupler.
In embodiments of the invention in which the input optical
25   splitter 40 is a 2x2 3-dB single-mode fiber coupler, the input
optical signal is input at one of the two inputs of the 2x2
3-dB single-mode fiber coupler and the other input of the 2x2
3-dB single-mode fiber coupler is terminated. In other
embodiments of the invention, the input optical splitter 40 is

a micro-optical coupler or any type of optical device capable of producing the required function.

Optical Transmission Media

In the preferred embodiment of Figure 1, the optical transmission media 41 and 42 are optical fibers. In another embodiment of Figure 1, the optical transmission media 41 and 42 are waveguides. An optical signal that propagates through the optical transmission medium 41 undergoes a phase spread, $\varphi_1(\vec{r})$. Similarly, another optical signal that propagates through the transmission medium 42 undergoes a phase spread, $\varphi_2(\vec{r})$. The phase controllers 50 and 60 are used to fine tune the phase spreads $\varphi_1(\vec{r})$, $\varphi_2(\vec{r})$ respectively.

A phase difference, $\varphi_1(\vec{r}) - \varphi_2(\vec{r})$ is introduced partially by the optical transmission media 41,42 per se and partially by the phase spreads introduced by the phase controllers 50,60. The component introduced by the optical transmission media 41,42 per se may be due to different physical lengths of the media and/or different indexes of refraction of the media. Recalling that the overall phase difference at the combination point (the output optical coupler 70) can be expressed as $\varphi_1(\vec{r}) - \varphi_2(\vec{r}) + \varphi_{10} - \varphi_{20}$, a coarse phase adjustment of the phase difference, $\varphi_1(\vec{r}) - \varphi_2(\vec{r}) + \varphi_{10} - \varphi_{20}$ can be achieved by first choosing different respective physical lengths of the optical transmission media 41 and 42 and/or by using lengths of optical transmission media having different respective nominal index of refraction. Fine adjustment of the overall phase difference $\varphi_1(\vec{r}) - \varphi_2(\vec{r}) + \varphi_{10} - \varphi_{20}$ is performed using the phase controllers 50,60.

Phase Controllers

The phase controllers 50,60 may be any devices capable of introducing in a controllable manner the required fine phase spread into the overall phase spread experienced by signals propagating in the optical transmission media 41,42. In one embodiment of the invention, the phase controllers 50 and 60 are heaters and the fine phase adjustment is done by changing the indexes of refraction of at least portions of the optical transmission media 41 and 42 by heating one or both of the optical transmission media 41 and 42.

In another embodiment, the phase controllers 50,60 are adapted to apply a stretching force to at least portions of one or both of the optical transmission media 41 and 42. This can be achieved for example through the use of piezo-electric devices.

In the embodiment of Figure 1, the fine phase spread is implemented through a combination of the two phase controllers 50 and 60. In another embodiment, the fine phase spread is implemented through the use of only a single phase controller, for example phase controller 50 in which case phase controller 60 is not required. However, it is noted that the use of both phase controllers 50 and 60 allows the phase difference to be finely adjusted with more ease and accuracy.

In a preferred embodiment of the invention each one of the optical transmission media 41 and 42 has a constant nominal index of refraction throughout its length. Nominally, $\Delta L_o = n_1 L_1 - n_2 L_2$ where $L_1$ and $L_2$ are the physical lengths of the optical transmission media 41 and 42, respectively, and $n_1$ and $n_2$ are the indices of refraction of the optical transmission media 41 and 42, respectively. In another embodiment of the invention the indices of refraction of the optical transmission media 41 and 42 vary over the length of their respective

medium.  Consequently, $\Delta L_o = \int n_1(s_1)ds_1 - \int n_2(s_2)ds_2$.  For example,
each path may have a number of segments each having a length
and each having an index of refraction in which case

$\Delta L_o = \sum_{i=1}^{N_1} {}_i n_{1\,i} L_1 - \sum_{i=2}^{N_2} {}_i n_{2\,i} L_2$ where one of the optical transmission media

5 41,42 is composed of $N_1$ segments with the $i^{th}$ segment having
indices of refraction and lengths $\{{}_i n_1, {}_i L_1\}$.  Similarly, the other
optical transmission medium of the optical transmission media
41,42 is composed of $N_2$ segments with the $i^{th}$ segment having
indices of refraction and lengths $\{{}_i n_2, {}_i L_2\}$.  In this case, the
10 fine phase control can be achieved through appropriate
adjustment of any one or more of the indices of refraction ${}_i n_1, {}_i n_2$
and/or lengths ${}_i L_1, {}_i L_2$.  Furthermore, the indices of refraction
may vary continuously from one segment to another and/or within
a segment in which case the above presented integral
15 representation of $\Delta L_o$ is a more accurate representation.

Any deviations in the optical path length difference
$\Delta L_o$ from p2π will result in some of the coherent signal power
being output at subsidiary output 81 and lost.

Output Optical Coupler

20 The output optical coupler 70 is used as a
combination point for combining two path signals each with
intensity, $I/2$, but having a phase difference, $\delta$, between the
coherent path components at its two inputs.  As indicated
previously, the time-averaged intensity of the coherent path
25 component of the output optical signal at the main output of
the output optical coupler 70 is $I\langle\cos^2(\delta/2)\rangle$.  Therefore, two
coherent path signals at the first and second inputs of the
output optical coupler 70 that have a constant phase
difference, $\delta = \pm 2p\pi$ where $p = 0, \pm 1, \pm 2, \ldots$, are coupled entirely

into the main output 85 of the output optical coupler 70 with
intensity $I$, with no coherent signal strength being output at
the subsidiary output 81.  On the other hand, two independent
incoherent optical signals have an effective phase difference,

5    $\delta$, which is a random function of time.  In this case the two
independent incoherent optical signals are coupled equally into
the main output 85 and the subsidiary output 81, each with
intensity I/2.  In the preferred embodiment of Figure 1, the
output coupler 70 is a 2x2 3-dB single-mode fiber coupler with

10   a 50:50 coupling ratio.  More generally, any coupling device
capable of combining the coherent components, and splitting off
incoherent components to subsidiary outputs may be employed.

Design Constraints

        The coherent and incoherent path components of the
15   path signals that propagate through the transmission media
41,42 end up with a phase difference of $\varphi_1(\vec{r})-\varphi_2(\vec{r})+\varphi_{10}-\varphi_{20}$.  The
selection of this phase difference is made to ensure that the
incoherent path components of the two path signals are not
correlated at the point where recombination is to take place

20   and to ensure that the coherent components combine
constructively.  The phase difference can be expressed as an
optical path length difference, $\Delta L_o$.

A) Incoherence Length

        Preferably, to ensure the incoherent path components
25   are substantially uncorrelated, the optical path length
difference, $\Delta L_o$, is selected to be greater than the coherence
length, $L_c$, of the incoherent path components of the path
signals ($\Delta L_o > L_c$).  The choice $\Delta L_o > L_c$ assures that the
incoherent path components of the two path signals are

30   independent and thus have a random phase difference between
them and ensures that any incoherent path components are split

approximately evenly between the main and subsidiary outputs of the output optical coupler. If $\Delta L_o$ is less than $L_C$, then it is possible that some fraction less than 50% of the incoherent component will be directed to the subsidiary output. This will

5　reduce the SNR improvement, but may still yield a workable design.

Constructive Combination

The optical path length difference, $\Delta L_o$, expressed as a phase difference is $\varphi_1(\vec{r})-\varphi_2(\vec{r})+\varphi_{10}-\varphi_{20}$. This quantity is

10　selected such that the phase difference satisfies $\varphi_1(\vec{r})-\varphi_2(\vec{r})+\varphi_{10}-\varphi_{20} = 2p\pi$ where $p=0,\pm1,\pm2,...$, for the wavelength(s) of interest with the result that the coherent path components are coupled into the output 85 and combined constructively. While there are many phase differences that satisfy $2p\pi$, p = $\pm1$,

15　$\pm2,...$, some of these are eliminated for failing to satisfy the coherence length constraint. Typically, the coherence length constraint requires the phase difference to satisfy $2p\pi$, where p is an integer with $|p| > P_{min}$.

The intensity of the coherent component of the output

20　signal is equal to the intensity of the coherent component of the input signal except for minor insertion losses in the input and output couplers 40 and 70, respectively, and the two phase controllers 50 and 60. On the other hand, the intensity of the incoherent component of the output optical signal is

25　approximately one-half the intensity of the incoherent component of the input optical signal. Consequently, the SNR of the input optical signal is therefore increased by a factor of approximately 2.

## B) Symbol Spread Tolerance

When the coherent components are split and then recombined, one of the coherent components is delayed with respect to the other. This results in a slight spreading of
5    the symbols being carried by the recombined coherent component. The symbol rate applies another condition which limits the optical path length difference to $\Delta L_0 \leq \chi C/R$, where $C$ is the speed of light in vacuum; R is the symbol rate of the optical signals and $\chi$ is a fraction indicating a maximum symbol spread
10   to which the system is tolerant. For example, $\chi = 0.2$ indicates a 20% tolerance. This requirement is put in place to avoid the effects of smearing/dispersion which would result should the coherent components be so different in phase that a substantial symbol spread occurs.

15   Multi-channel Applications

For single wavelength applications, the case in which the SNR of the input optical signal is increased by a factor of approximately 2 requires that $\delta = 2p\pi$ where $p = 0, \pm 1, \pm 2, ...,$. The method can also be used in multi-channel applications, in which
20   case the input optical signal has a plurality of equally spaced (with respect to frequency) channels wherein any two consecutive channels with input wavelengths $\lambda'$ and $\lambda$ differing by a spectral difference, $\Delta\lambda = \lambda' - \lambda$. To ensure the constructive recombination of all the wavelengths simultaneously at the
25   combination point, the method requires that the optical path length difference, $\Delta L_o$, satisfies $\Delta L_o = K\lambda\lambda' / 2(\Delta\lambda)$, where $K = 1, 2,$ 3, ... . Equivalently, this condition is satisfied by two consecutive channels of frequency $f'$ and $f$ simultaneously when $\Delta L_o = KC/(2\Delta f)$, where $K = 1, 2, 3, ...,$ $C$ is the speed of light in
30   vacuum and $\Delta f = f' - f$. Therefore, the noise reduction apparatus

10 separates a number of periodically spaced channels of the
input optical signal at its input 5 and outputs the respective
channels at its output 85 with each channel having an increase
in SNR by a factor of approximately 2. For example, a channel

5    space of 100 GHz around $\lambda$=1550-nm with an optical path length
difference of 1 mm, 2 mm, 3 mm, 4 mm or 5 mm is practical and
satisfies OC192 networking systems. If the optical path length
difference, $\Delta L_o$, is too long OC192 networking systems
requirements are not satisfied. The optical path length

10   difference, $\Delta L_o$, may also be chosen to be approximately equal to
1 mm or less to satisfy requirements of future OC768 networking
systems.

     Referring to Figure 2, shown is a noise reduction
apparatus 15 provided by a second embodiment of the invention.

15   The noise reduction apparatus 15 includes $N$ noise reduction
apparatuses 10,110 (only two shown), which are each similar to
the noise reduction apparatus 10 of Figure 1. The $N$ noise
reduction apparatuses are connected in series such that an
output of one of the $N$ noise reduction apparatuses is connected

20   to an input of a consecutive noise reduction apparatus of the $N$
noise reduction apparatuses. A final noise reduction apparatus
110 of the $N$ noise reduction apparatuses has an output 185
which corresponds to an output of the noise reduction apparatus
15.

25       An input optical signal is input at the input 5 and
propagates through the $N$ noise reduction apparatuses, two of
which are the apparatuses 10 and 110, and is output at the
output 185. The intensity of a coherent component of the input
optical signal remains largely unaffected at the output 185.

30   On the other hand, the intensity of a incoherent component of
the input optical signal is decreased by a factor of
approximately $2^N$ at the output 185. Consequently, the SNR of

the input optical signal is increased by a factor of

approximately $2^N$, or 3N dB.

Referring to Figure 3, shown is a noise reduction

apparatus 115 provided by a third embodiment of the invention.

5    The noise reduction apparatus 115 has an input 205 connected to

an input optical splitter 240. In the preferred embodiment of

Figure 3, the input optical splitter 240 is a 1x$M$ coupler and

has one input and $M$ outputs (only three shown). In another

embodiment of Figure 3, the input optical splitter 240 is an

10   $M$x$M$ coupler and has $M$ inputs and $M$ outputs. There are $M$

optical transmission media (only three shown), three of which

are optical transmission media 241, 242 and 243. Each one of

the $M$ optical transmission media is connected between one of

the $M$ outputs of the input optical splitter 240 and one of $M$

15   inputs (only three shown) of an output coupler 270. The

optical lengths of the $M$ optical transmission media are chosen

such that the optical path length difference, $\Delta L_o$, between any

two of the $M$ optical transmission media is greater than the

coherence length, $L_c$, of incoherent path components of $M$ path

20   signals propagating through the respective $M$ optical

transmission media. Each one of the $M$ transmission media

passes through a phase controller (only three shown). The

optical transmission media 241, 242 and 243 pass through phase

controllers 251, 252 and 253, respectively. The output optical

25   coupler 270 is a $M$x$M$ coupler that has $M$ outputs (only three

shown) one of which is the main output 285 of the noise

reduction apparatus 115. The remaining $M$-1 outputs 271, 272

are subsidiary outputs terminated locally (only two shown).

The outputs 271 and 272 are terminated locally.

30           In the preferred embodiment of Figure 3, each one of

the $M$ optical transmission media passes through a respective

one of the $M$ phase controllers. In another embodiment of

Figure 3, there are $M$-1 phase controllers and all but one of the $M$ optical transmission media passes through a respective one of the $M$-1 phase controllers. Preferably, there is at least one phase controller.

5    In the preferred embodiment of Figure 3, an input optical signal is input at the input 205. The input optical signal has a coherent component and an incoherent component (noise) with intensities, $I_C$ and $I_N$, respectively. The input optical splitter 240 splits the input optical signal into $M$
10   path signals. Each one of the $M$ path signals has a coherent and incoherent path component. The coherent path components of the path signals have the same intensity, $I_C/M$, but vary in phase with a phase difference, $\varphi_{i0} - \varphi_{j0}$ where $i, j = 1, 2, ..., M$, between any two path signals of the $M$ paths. Similarly, the
15   incoherent path components of the two path signals have the same intensity, $I_N/M$. The coherent and incoherent path components of each of the path signals propagate through a respective one of the $M$ optical transmission media and undergo a phase spread, $\varphi_i(\vec{r})$ ($i$ = 1 to $M$). For example, the coherent
20   and incoherent components of three path signals propagate through a respective one of the optical transmission media 241, 242 and 243 and undergo phase spreads, $\varphi_1(\vec{r})$, $\varphi_2(\vec{r})$ and $\varphi_3(\vec{r})$, respectively. The $M$ phase controllers perform a fine phase adjustment of a phase $\varphi_i(\vec{r})$ ($i$ = 1 to $M$) such that a phase
25   difference, $\delta = \varphi_i(\vec{r}) - \varphi_j(\vec{r}) + \varphi_{i0} - \varphi_{j0}$ ($i$, $j$ = 1 to $M$), between any two of the coherent path components of the M path signals satisfies $\delta$ = $2p\pi$ where $p = 0, \pm 1, \pm 2, ...$. After propagating through the $M$ phase controllers the respective path signal then propagates to a respective input of the $M$ inputs of the output
30   optical coupler 270. At the output optical coupler 270 the coherent path components of the $M$ path signals are combined

constructively such that the intensity of a coherent component
of an output optical signal at the output 285 is approximately
equal to $I_C$.   In addition, at the output optical coupler 270 the
incoherent path components of the $M$ path signals are coupled

5    equally into the $M$ outputs such that the intensity of the
incoherent component of the output optical signal at the output
285 is approximately equal to $I_N/M$.

The intensity of the coherent component of the output
optical signal is equal to the intensity of the coherent

10   component of the input optical signal except for minor losses
in the input optical splitter 240 and the coupler 270,
respectively, the optical transmission media 41,42 and the $M$
phase controllers.   On the other hand, the intensity of the
incoherent component of the output signal is reduced by a

15   factor of approximately $M$ of the intensity of the incoherent
component of the input optical signal.   Consequently, the SNR
of the input optical signal is therefore increased by a factor
of approximately $M$.

In another embodiment of Figure 3, $N$ noise reduction

20   apparatuses similar to the noise reduction apparatus 115 are
connected in series such that an output of one of the $N$ noise
reduction apparatuses is connected to an input of a consecutive
noise reduction apparatuses of the $N$ noise reduction
apparatuses.   In this embodiment, the SNR ratio of an input

25   optical signal propagating through the $N$ noise reduction
apparatuses is increased by a factor of approximately $M^N$
resulting in an increase in SNR of approximately $10N(\log M)$ dB.

Referring to Figure 4, shown is a noise reduction
apparatus 410 provided by a fourth embodiment of the invention.

30   The noise reduction apparatus 410 has an input 405 and an
output 485.   The input 405 and the output 485 are connected to

a coupler 440. Optical transmission media 441 and 442 are connected to the coupler 440. The optical transmission media 441 and 442 are also connected to reflectors 470 and 475, respectively. In addition, the optical transmission media 441

5 and 442 pass through phase controllers 450 and 460. An optical optical isolator 480 is connected to the input 405 of the noise reduction apparatus 410.

In the preferred embodiment of Figure 4, the coupler 440 is a 2x2 3-dB single-mode fiber coupler and the reflectors

10 470 and 475 are broadband fiber gratings. In another embodiment, the coupler 440 is a 2x2 single-mode micro-optics coupler and the reflectors 470 and 475 are different types of reflectors such as gold tip pig tail fiber reflectors.

In a preferred embodiment of the invention of Figure

15 4, an input optical signal is input at the input 405. The input optical signal has a coherent component and an incoherent component with intensities, $I_C$ and $I_N$, respectively. The coupler 440 splits the input optical signal into two path signals with each path signal having a coherent path component and

20 incoherent path component with intensities, $I_C/2$ and $I_N/2$, respectively. The coherent path components of the two path signals have a phase difference, $\varphi_{10} - \varphi_{20}$, which is a constant whereas the incoherent path components of the two path signals have a phase difference, $\varphi_{10} - \varphi_{20}$, which is a random function of

25 time. Each one of the two path signals performs a round trip propagating through its respective phase controller of the phase controllers 450 and 460 to its respective reflector of the reflectors 470 and 475 where it is reflected; and back through its respective phase controller of the phase

30 controllers 450 and 460 to the coupler 440. A path signal of the two path signals that performs a round trip by passing through the phase controller 450 undergoes a phase adjustment,

$\varphi_1(\vec{r})$ and a path signal of the two path signals that performs a round trip by passing through the phase controllers 460 undergoes a phase adjustment, $\varphi_2(\vec{r})$, resulting in a phase difference, $\varphi_1(\vec{r})-\varphi_2(\vec{r})$. An optical path length difference, $\Delta L_o$,

5 associated with the phase difference, $\varphi_1(\vec{r})-\varphi_2(\vec{r})$, is selected to be greater than the coherence length, $L_c$, of the incoherent components of the path signals. After a round trip the two path signals each have coherent path components with intensity, $I_C/2$, and incoherent path components with intensity, $I_N/2$ at the

10 coupler 440. At the coupler 440 the coherent path components of the two path signals have a phase difference, $\delta = \varphi_1(\vec{r})-\varphi_2(\vec{r})+\varphi_{10}-\varphi_{20}=2p\pi$ where $p=0,\pm1,\pm2,\ldots$, whereas the effective phase difference, $\delta$, between the incoherent path components of the two path signals, is a random function of

15 time. The coupler 440 combines the two path signals into output optical signals that are output at output 485 and input 405.

The intensities of the coherent and incoherent path components of the output signal at output 485 are given by

20 $I_C\langle\cos^2(\delta/2)\rangle$ and $I_N/2$, respectively, and intensities of the coherent and incoherent path components of the output signal at input 405 are given by $I_C\langle\sin^2(\delta/2)\rangle$ and $I_N/2$. The phase controllers 450 and 460 perform a fine phase adjustment such that $\delta=2p\pi$ where $p=0,\pm1,\pm2,\ldots$, at the coupler 440. Therefore,

25 with proper tuning $\delta$, at output 485, the coherent path components of the two path signals combine constructively with intensity, $I_C$ at output 485 and input 405. Since the optical path length, $\Delta L_o$, is greater than the coherence length of the incoherent path components of the two path signals, they couple

30 with intensity, $I_N/2$, into output 485 and input 405. Consequently, the SNR of the input optical signal at the input

405 is increased by a factor of approximately 2 at the output
485. The optional optical isolator 480 suppresses the output
optical signal at the input 405.

5      Referring to Figure 5, shown is a flow chart of a
preferred method of selecting a phase difference for use in the
apparatus of Figure 1. The method starts with the
identification of a single wavelength of interest $\lambda$, or the
identification of a set of wavelengths of interest having
constant frequency spacing $\Delta f$ between any two consecutive
10     wavelengths (step 5-1). In the following steps the coherence
length, $L_c$, of the M path signals is determined (step 5-2) and
the maximum symbol spread the coherent path components can
tolerate (step 5-3). An optical path length difference between
any two coherent path components is selected by choosing a
15     phase difference such that an optical path length difference,
$\Delta L_o$, satisfies the following criteria: 1) $\Delta L_o > L_c$ where $L_c$ is a
coherence length of the incoherent path components of the $M$
path signals (step 5-4); 2) $\Delta L_o$ selected for satisfactory symbol
spread (step 5-4); 3) For single wavelength applications, a
20     phase difference is selected associated with any two paths of
the $M$ path signals, resulting in a phase difference, $\delta = 2p\pi$
where $p = 0, \pm 1, \pm 2, \ldots$, between the coherent components of any two
of the $M$ path signals at a combination point (step 5-5); 4) For
multiple wavelength applications, $\Delta L_o = KC/(2\,\Delta f)$ (step 5-6) where,
25     $\Delta f = f' - f$ and, $f'$ and $f$ are the frequencies of two consecutive
channels of the input optical signal. For single wavelength
applications, the simultaneous satisfaction of all the
constraints involves the proper selection of p. To satisfy
these three constraints simultaneously for multiple wavelength
30     applications involves the proper selection of $K$.

In a preferred embodiment $M = 2$ and $N = 1$ resulting
in an increase in the SNR of the input optical signal of
approximately 2 and an increase in the SNR of approximately 3
dB.

5       In yet another way of implementing this invention,
the noise reduction apparatus can be implemented with $M$ paths,
and within each of the $M$ paths, a further noise reduction
apparatus having $N_i$ paths may be provided to improve the SNR of
a respective one of the $M$ path signals.

10      In some implementations, the noise reduction
apparatuses described above are further equipped with a power
detector connected to at least one subsidiary output of the
noise reduction apparatus and to a control device. The power
detector converts the subsidiary optical signal into a signal
15 representative of the power of the subsidiary optical signal.
The control device is adapted to control at least one of the
phase adjustments applied to the path signals as a function of
the output of the power detector. Assuming that the phase
adjustments result in the required characteristic of
20 uncorrelated incoherent components, this control function
minimizes the power in the subsidiary optical signal which in
turn minimizes the coherent power in the subsidiary optical
signal, which in turn maximizes the coherent power in the main
output.

25      Numerous modifications and variations of the present
invention are possible in light of the above teachings. It is
therefore to be understood that within the scope of the
appended claims, the invention may be practised otherwise than
as specifically described herein.